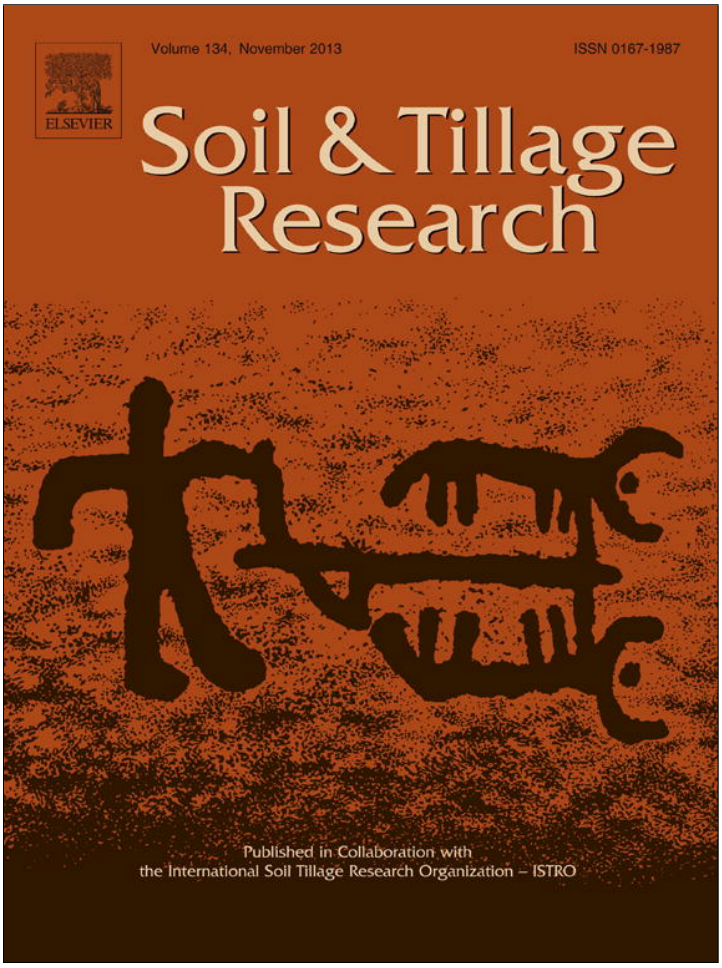
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Complementary irrigation and direct drilling have little effect on soil organic carbon content in semiarid Argentina

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ABSTRACT

Irrigation and tillage modify soil properties. The aim of the present study was to evaluate the simultaneous effect of complementary irrigation and zero tillage (ZT) on soil organic carbon (SOC). Two treatments (irrigated and rain fed soils) were evaluated in a field experiment set up in Manfredi, Córdoba province, Argentina. The soil was grid-sampled at the beginning of the experiment in 1996 and soil organic carbon (SOC), aggregate stability (AS), bulk density (BD), electrical conductivity (EC) and exchangeable sodium percentage (ESP) were determined in 2007. In the irrigated treatment SOC tended to increase on the surface layer in the irrigated experiment. The increase in SOC stock was estimated as 0.221 tn C/ha/year but higher C-CO_2 emission also occurred. The AS of the surface horizon was higher under irrigation, associated with SOC and soil EC. The quasi-equilibrium in SOC was explained by a greater intake of crop residues counteracted by an increased biological activity in the irrigated soil.

1. Introduction

The balance between carbon (C) inputs and outputs determines the content of organic carbon in soils (SOC). The main carbon inputs are plant residues, animal manure and other minor sources, while the main outputs are the microbial degradation of organic compounds and erosion (Davidson and Ackerman, 1993). Most cultural practices affect the SOC balance and tend to a new equilibrium, generally with lower SOC content than the original one (Davidson and Ackerman, 1993). Soil organic matter as a sink of atmospheric carbon is, at present, of major interest to mitigate the Global Climate Change. Many studies have measured or estimated the soil carbon sequestration under different climatic, soil and management conditions (Bruce et al., 1999; Lal et al., 1999; Liang et al., 2005; Schulp et al., 2008). Management practices tending to increase the crop residue input can favorably change the SOC balance (Denef et al., 2008). Conservation tillage, especially direct drilling and irrigation, tends to increase the SOC stock (Álvarez, 2005).

In the long term, direct drilling causes a large transformation in the soil environment (Arshad et al., 1999; Hernanz et al., 2002). Crop residues remain on the soil surface and organic compounds tend to accumulate on the soil top layer (Unger, 1991; Álvarez et al., 1995; Díaz Zorita et al., 2002; Kay and VandenBygaart, 2002). Most studies has shown the SOC stratification but the global SOC increases would be of low magnitude and would occur in the long term (Álvarez, 2005; Álvarez et al., 1995; Angers et al., 1997; Arshad et al., 1996; Kay and VandenBygaart, 2002). Factors affecting this process are crop rotations (Díaz Zorita et al., 2002; Huggins et al., 2007) and soil and climate characteristics (Franzluebbers and Arshad, 1996; Buschiazzo et al., 1998). Direct drilling very often decreases total porosity of the top soil, due to the reduction in soil macropores. This has been attributed to the lack of soil movement, the machinery traffic and depends of the soil texture (Chang and Lindwall, 1992; Buschiazzo et al., 1998; Sasal et al., 2006). Direct drilling also leads to a higher aggregate stability (Buschiazzo et al., 1998; Micucci and Taboada, 2006). Silty soils are the most affected due to the lack of structure self-regeneration as compared with clayey soils (Taboada et al., 1998).

Irrigation, especially with sodium-rich water, also modifies soil properties. One of the main degradation processes due to irrigation is soil alkalinization, which causes clay dispersion and swelling, and negatively affects soil aggregation (Frenkel et al., 1978; Pilatti et al., 2006; Shaimberg et al., 2001). Soil alkalinization also causes the dispersion of humified organic matter. This organic fraction, known as soluble organic carbon (SolOC), has been studied both in the field (Lavado and Alconada, 1994; Peinemann et al., 2005) and in the laboratory (Kalbitz et al., 2000; Oste et al., 2002). The dissolution of crop residues also leads to SolOC (Kalbitz et al., 2000; Chantigny, 2003). Jueschke et al. (2008) found that long-term

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irrigation increases the SolOC concentration in soil depth. Barzegar et al. (1997) found that even with high exchangeable sodium, SOC influences soil structural stability.

The effect of irrigation on SOC balance is far from linear, because there are two opposite processes. On the one hand, irrigation increases crop yield, which usually causes more crop residues, which in turn may result in an increase in soil SOC (Lal et al., 1999; Gillabel et al., 2007; Denef et al., 2008; Wu et al., 2008). On the other hand, irrigation increases microbial activity due to higher soil water content, which can accelerate the mineralization of carbon compounds, increasing CO_2 fluxes toward the atmosphere (Gillabel et al., 2007; Jabro et al., 2008; Sainju et al., 2008). Both processes could neutralize each other and in many locations the gains of SOC in irrigated soils are of very low magnitude or even negligible (De Bona et al., 2008; Ricks Presley et al., 2004; Verma et al., 2005).

The aim of present study was to quantify changes in SOC and related properties in the field due to application of irrigation with alkaline water, on a direct drilled silty soil. Treatments were applied for 11 years and wheat, soybean and maize were cropped.

2. Materials and methods

2.1. Study area

The study area is located in Córdoba province (Argentina). The area is semiarid (annual rainfall average 757 mm), showing a Monzonic-like regime. Predominant soils are silty (68–70% silt) with low SOC (Jarsun et al., 1987). The area, historically devoted to cattle husbandry, has been devoted to agriculture, mainly sorghum, maize, sunflower and groundnut, since 1980. Soybean has been the main crop from the last 10 years. The tillage system changed from conventional to conservation tillage and, in the last years, to direct drilling (AAPRESID, 2010). Complementary irrigation was adopted in the 1990 decade and at present more than 110,000 ha are irrigated using central pivot, linear or hose reel traveler irrigation systems. The potential for irrigation is high because the groundwater reserves would allow irrigating around 1,500,000 ha (Rampoldi et al., 2010).

2.2. Experimental

The study consisted of a long-term experiment carried out at Manfredi Experimental Station (INTA), 31.6° S, 63.7° W, altitude above sea level 292 m. The soil was classified as Oncativo Series, coarse silt, mix, thermic Entic Haplustoll. Underground water, taken at 125 m depth, was used for irrigation. The water is standard in the region (EC: 1.07 dS/m and SAR: 7.5) (Rampoldi et al., 2010).

The experiment started in 1996 on a previously conventionally tilled soil. The experiment followed a standard crop sequence for the area (wheat/soybean–maize) performed on a two-year basis on direct drilling. The plot covers 40 ha. Complementary irrigation was carried out by central pivot equipment in a round area of 28 ha (irrigated treatment). The remaining 12 ha received the same management as the irrigated area but were rain fed (rain fed treatment). Wheat was seeded and harvested in June and December, soybean in December and May, and maize in October and March.

Soybean was fertilized with ammonia phosphates (MAP or DAP) at seeding, whereas wheat and maize were fertilized with nitrogen liquid fertilizer (UAN injected in the irrigation water in two applications) and MAP or DAP. Annual doses of nitrogen were, on average, 100–120 kg/ha/year (irrigated treatment) and 60–70 kg/ha/year (rain fed treatment) for wheat and 130 kg/ha/year (irrigated treatment) and 80 kg/ha/year (rain fed treatment) for maize, whereas annual doses of phosphorus were 17 kg/ha/year for wheat and for maize, and 14 kg/ha/year for soybean. To determine the irrigation moment and the water sheet, the water accumulated in the soil profile, the water needed for each crop, the evapotranspiration and the effective rainfall were taken into account. Wheat received annually on average 207 mm, maize 152 mm and soybean 98 mm. The crop was harvested with a combine harvester, equipped with a yield monitor. The average crop yield is shown in Table 1. Yields of irrigated crops were on average 100%, 40% and 25% higher than those of rain fed crops for wheat, maize and soybean, respectively. The soil of the whole plot was sampled at the beginning of the experiment, in 1996. To this end, a square design of 60 m of side was set and 106 sampling points were geopositioned. In each point, a composite sample was taken at two depths: 0–20 cm and 20–40 cm.

The landscape of the experimental plot was uneven. Then it was divided in four sectors and each sector was taken as a block. The SOC values determined in 1996 were highly related to the location within the plot. This was taken into account when results were statistically analyzed. In 2007, soil samples were taken following the initial square design. In this case, 78 points (56 irrigated and 22 rain fed) were sampled. Composite samples were taken at 0–10 cm, 10–20 cm, 20–40 cm and 40–80 cm depth. Samplings were carried out after the summer crops were harvested.

The following parameters were determined on each of those samples: Soil organic carbon (SOC), by the Walkley & Black method (Sparks et al., 1996); soluble organic carbon (SolOC), extracted from a 1:2 soil:water suspension according to Mazzarino et al. (1993); electrical conductivity (EC) and pH on 1:2.5 soil:water ratio; exchangeable sodium and cation exchange capacity (Sparks et al., 1996) and exchangeable sodium percentage by the formula ESP = (exchangeable Na/CEC) × 100. It was also determined:

- Bulk density (BD), by the cylinder method (Burke et al., 1986). Cylinders were 100 cm^3 and sampling was carried out at 0–6 cm, 6–12 cm and 12–18 cm depth. In each point, sampling was carried out in duplicate.
- SOC stock per area unit, corrected for equivalent mass of soil at 0–10 cm and 0–20 cm depth (Ellert and Bettany, 1995). A total of 14 points in the irrigated treatment and 10 in the rain fed treatment were selected from the initial square design and BD was determined as mentioned above. Soil mass was calculated using the average BD in both treatments and then the equivalent mass of the soil profile in both treatments at 20 cm depth (Ellert and Bettany, 1995). From the corrected soil mass and the SOC concentration, the SOC stock per area unit was calculated in each point.
- Aggregate stability (AS). In each point, undisturbed sampling was carried out in duplicate at 0–6 cm, 6–12 cm and 12–18 cm depth. Samples were disaggregated and dried for seven days at room temperature. Dry samples were automatically sieved by 1 and 2 mm sieve for 30 s. In macroaggregates of 1 and 2 mm diameter, stability was determined by the wet sieving method).

Table 1
Grain yields (average 1996–2007) in biannual crop sequence and annual C input of crop residues (roots and straw) for irrigated and rainfed crops, in both the irrigated a rainfed treatments.

Crops	Grain yield (tn/ha/year)		Carbon input (tn/ha/year)	
	Irrigated	Rainfed	Irrigated	Rainfed
First year				
Wheat	4.67	2.04	3.73	1.63
Soybean	2.94	2.51	2.16	1.85
Second year				
Maize	11.74	8.53	4.70	3.41

2.3. Statistical analysis

Data of SOC, SOC stock, SolOC, BD and AS obtained in 2007 were analyzed using an ANOVA with a linear mixed model that included a treatment factor "irrigation vs. rain fed", which allowed modeling the spatial correlation among observations with an exponential model. The variance and co-variance structures were considered homogeneous. The different levels of treatments were compared with *a posterori* LSD test, with a significance of 0.05. An ANOVA with a linear mixed model was used to analyze the temporal evolution of SOC. In this case, the factor "year of measurement" (1996 and 2007) was also included. The analyses were performed at each depth, with a posteriori LSD test, with a significance of 0.05. After that, the variation between 1996 and 2007 was calculated as the difference between the SOC measured in 2007 and that measured in 1996, for each treatment. A linear mixed model was adjusted as described. The relationship between AS data and SOC, EC and ESP data were obtained comparing data from 0–6 cm depth to 0–10 cm depth and 12–18 cm depth to 10–20 cm depth. Linear multiple regressions were determined among the measured variables. All analyses were carried out using the InfoStat statistical analysis (Di Rienzo et al., 2009).

3. Results

Soil OC values in 2007 are shown in Fig. 1. There were no statistical differences between the irrigated and the rain fed treatments at any depth. However, SOC tended to show a higher concentration in the irrigated treatment ($p < 0.1$) at 0–10 cm and 40–80 cm depth. The SolOC was higher in the irrigated treatment ($p < 0.05$) in all soil layers and tended to decrease toward deeper layers (Fig. 2), while the highest differences between treatments were found at 0–40 cm depth. There was a highly positive relation between the concentrations of SOC and SolOC. The variations in SOC explained around 84% of SolOC variations ($p < 0.0001$) (Fig. 3). SolOC was positively related to the SOC concentration and the soil ESP (see below) (i.e. at 0–10 cm depth SolOC = 46.6 + 54.3SO-C + 5.2ESP; $p < 0.0001$; R^2 0.67). Both variables explained 67–51% at 40 cm depth. In the deepest layer (40–80 cm), SolOC was related only to ESP (SolOC = 48.3 + 0.9ESP; $p < 0.05$; R^2 0.10) but this variable explained only 10% of variability.

The comparison between the SOC data obtained in 1996 and those obtained in 2007 is shown in Fig. 4. The treatment × time interaction was not significant ($p = 0.37$) at 0–20 cm depth. This means that at the start of the experiment (1996), SOC values were the same in both treatments. In 2007, SOC showed no significant increases in either treatment but tended to show a higher concentration ($p < 0.10$) in the irrigated treatment. Conversely,

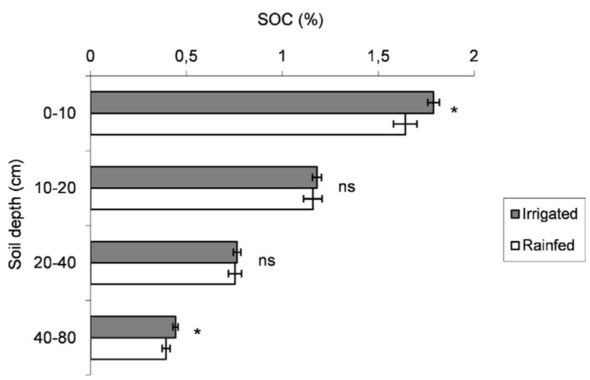

Fig. 1. Soil organic C concentration on 2007 sampling, for irrigated and rain fed treatments. ns = not significant. Asterisk (*) indicates significant differences ($p < 0.1$) among the same depth. Bars represent standard errors.

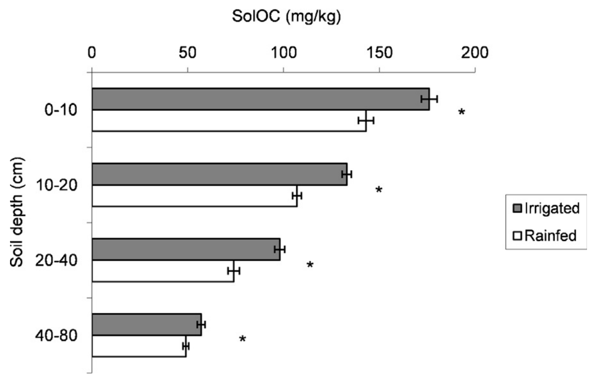

Fig. 2. Soluble organic C concentration on 2007 sampling, for irrigated and rain fed treatments. Asterisk (*) indicates significant differences ($p < 0.05$) among the same depth. Bars represent standard errors.

at 20–40 cm depth, there was significant ($p < 0.05$) treatment × time interaction. In 1996, SOC was higher in the rain fed treatment, whereas in 2007, SOC showed no significant differences between treatments, which indicate a significant decrease in SOC in the rain fed treatment.

Initially (1996), the SOC concentration at 0–20 cm depth was similar between both treatments; then, it can be assumed that the SOC stock was also the same between both treatments. The SOC stock in 2007 showed no significant differences between treatments at 0–20 cm depth but the irrigated treatment showed a tendency ($p < 0.10$) to higher SOC accumulation (the SOC in tn ha^{-1} was: Irrigated 37.75(±0.63) and rain fed 35.32(±1.35). The SOC stock comparing treatments increased at 2.43 tn C/ha in 11 years of complementary irrigation, i.e. 0.221 tn C/ha/year. The C from plant residues (straw + roots) is shown in Table 1. The irrigated treatment added more C from residues after harvest (5.30 tn C/ha/year) than the rain fed treatment (3.44 tn C/ha/year). This is an annual average of 1.86 tn C/ha/year of residues but would accumulate only 0.221 tn C/ha/year. This means that the soil would only accumulate 12% of the total C added by crop residues and that the CO_2-C loss to the atmosphere from the 0 to 20 cm depth via residue decomposition and mineralization would be higher in the irrigated treatment. In this treatment, around 1.64 tn C-CO_2/ha/year was lost by mineralization, a value higher than that from the rain fed treatment.

Electrical conductivity varied from 0.23 to 0.29 dS/m in the irrigated treatment and from 0.12 to 0.22 dS/m in the rain fed

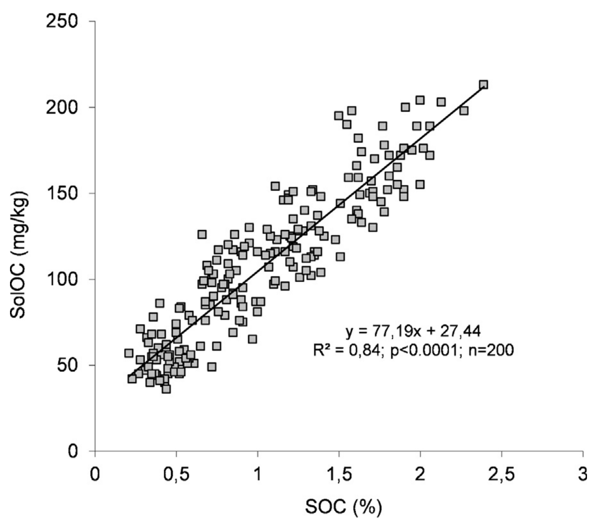

Fig. 3. Relationship between soil organic C and soluble organic C for the 0–80 cm depth, in both the irrigated a rain fed treatments.

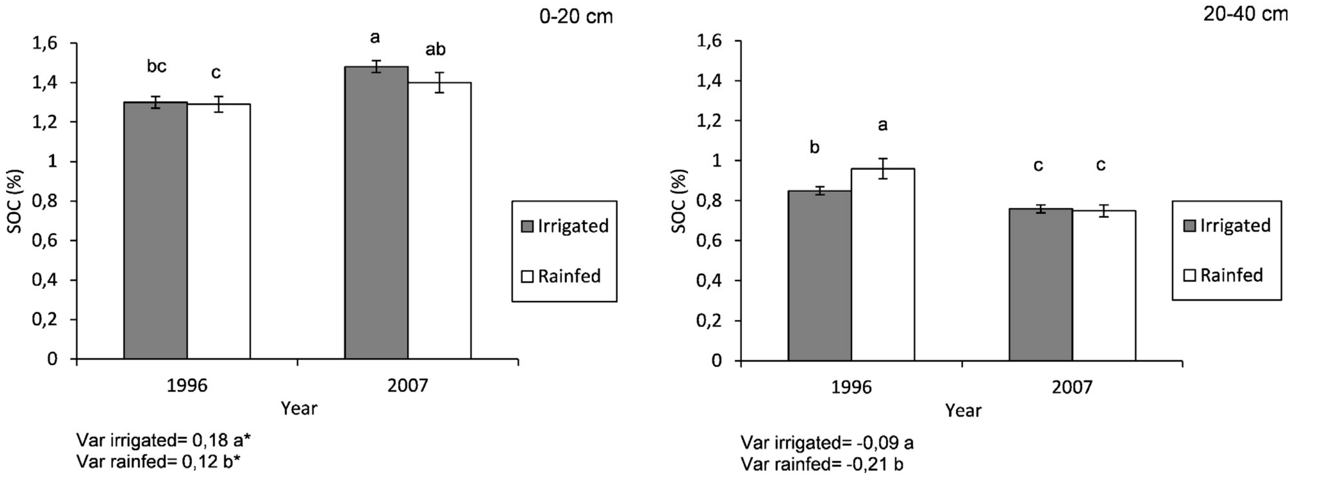

Fig. 4. Soil organic C concentration measured in 1996, 2007 and the variation between 1996 and 2007, for irrigated and rain fed treatments, at 0–20 cm and 20–40 cm depth. Var = variation between 1996 and 2007. Values followed by different lowercase letters statistically differ between treatments ($p < 0.05$). Asterisk (*) indicates significant differences ($p < 0.1$). Bars represent standard errors.

treatment on the soil profile in 2007. ESP varied from 6.0 to 7.8 in the irrigated treatment and from 1.7 to 2.3 on in the rain fed treatment. BD increased with depth but it was always significantly higher ($p < 0.05$) in the irrigated treatment than in the rain fed treatment (Table 2). AS at 0–6 cm depth was higher than that obtained at 6–12 and 12–18 cm in both treatments. In the top layer, AS was significantly higher ($p < 0.05$) in the irrigated treatment. No significant differences were found in deeper layers (Table 2).

4. Discussion

The soil showed an increase in soil EC, but this increase was almost negligible due to the extreme low absolute values. Conversely, ESP increased significantly in the irrigated soils. The SOC content measured in present experiment was within the values normally found in the agricultural soils of the area (Jarsun et al., 1987). The SOC in both treatments showed the characteristic distribution of soil profiles subjected to continuous direct drilling for several years: SOC to increase in the top soil and the decrease in SOC in deeper layers (Kay and VandenBygaart, 2002; Follett, 2001; Unger, 1991; Verma et al., 2005).

The differences in SOC concentration and stocks between both treatments were of low magnitude. Results from previous studies in irrigated soils are sometimes contradictory. Denef et al. (2008) determined SOC stocks 10–12% higher in irrigated areas than in rain fed areas at 0–20 cm depth, after 34 years of direct drilling in wheat fields. Other authors also determined increases in SOC when soils were subjected to irrigation (Bhattacharyya et al., 2008; Lueking and Schepers, 1985; Zhao et al., 2007). Conversely, Ricks Presley et al. (2004) found no changes in SOC in the soil profile after 28–31 years of irrigation. Verma et al. (2005), De Bona et al. (2006), Martiniello (2007) and Nunes et al. (2007) found no increases in SOC in top soils due to irrigation. In the present experiment, at the top soil (0–20 cm depth), SOC showed a tendency to increase its concentration and stock in the soils subjected to irrigation compared with rain fed soils. The increase in SOC in soils subjected to irrigation can be explained by the increase in the quantity of crop residues added to the top soil layer (Denef et al., 2008; Gillabel et al., 2007). In deeper layers (20–40 cm depth), the SOC decrease was significantly lower in the irrigated treatment than in the rain fed treatment. The lower loss of carbon in the irrigated treatment could be explained by a higher root biomass in this soil (Wu et al., 2008). Blanco-Canqui et al. (2010) attributed the SOC redistribution in depth to an increase in SolOC caused by the irrigation water. In accordance, in the present experiment, the quantity of SolOC increased in the irrigated profile, especially at 40 cm depth (Fig. 2).

The higher concentration of SolOC in our irrigated soil was highly related to the SOC content and the ESP. Humified organic matter, such as fulvic acids, is one of the main sources of SolOC (Kalbitz et al., 2000; Lavado and Alconada, 1994; Peinemann et al., 2005). The release of SolOC is favored by increases in crop residues, high microbial activity and occurrence of soil fungi and any condition increasing organic matter mineralization (Kalbitz et al., 2000; Chantigny, 2003).

In irrigated conditions, crop yields increased but the decomposition and mineralization of organic compounds also increased. In the present experiment, only 12% of the additional C added by crop residues in the irrigated treatment would be accumulated on the top soil (0–20 cm depth). This explains the low magnitude of SOC stock increases in the irrigated treatment as compared to the rain fed treatment. In a similar experiment, Gillabel et al. (2007)

Table 2
Soil bulk density and aggregate stability on 2007 sampling, for irrigated and rainfed soils.

Depth (cm)	Treatment	Bulk density (g/cm^3)	Aggregate stability (%)
0–6	Irrigated	1.09 (±0.02) (a)	67 (±2) (a)
	Rainfed	1.03 (±0.02) (b)	48 (±3) (b)
6–12	Irrigated	1.42 (±0.01) (a)	36 (±2) (a)
	Rainfed	1.35 (±0.01) (b)	34 (±4) (a)
12–18	Irrigated	1.41 (±0.01) (a)	25 (±1) (a)
	Rainfed	1.35 (±0.01) (b)	28 (±2) (a)

Different letters indicate significant differences ($p < 0.05$) among the same depth and the same column. Standard error between brackets.

estimated a higher SOC mineralization in irrigated conditions due to an increase in microbial activity. This could be attributed to high water content in the soil for longer time, being soil water a main factor regulating SOC mineralization in the study area (Álvarez et al., 1995). Accordingly, increased CO_2 fluxes to the atmosphere have been measured either in conventional tillage or direct drilling in soils subjected to irrigation (Jabro et al., 2008; Sainju et al., 2008). De Bona et al. (2008) determined that the rewetting of dry soil which continuously happens in irrigated conditions favors biological activity and accelerates organic matter mineralization.

Bulk density data followed the normal pattern of the soil profiles in the area and were within the normal range for silty loam soils and did not affect root growth (Buschiazzo et al., 1998). The higher BD values found in the irrigated treatment could be accredited to more water content in the irrigated soils. During 2006/2007 and 2008, the average values of the water available in the soil at 80 cm depth were 93 mm and 72 for the irrigated and rain fed treatments, respectively. In that condition, the irrigated soil showed lower support capacity to heavy machinery. This explains the loss of total porosity (Taboada et al., 1998). The AS in the rain fed treatment was in the order of magnitude of that found in cropped soils of the region. The AS in the irrigated treatment was higher than rain fed treatment but still low when compared with data of AS higher than 90% found in a quasi-pristine top soil of the same soil Series and using the same methodology (Giubergia et al., 2010). The ESP was higher in the irrigated treatment than in the rain fed treatment, but structural stability was not negatively affected in this treatment. Linear regression ($AS = -78.6 + 41.8\ SOC + 263.9\ EC$, $p < 0.0001$; R^2 0.81) showed, in agreement with Pilatti et al. (2006), that high SOC values and soil salinity counteract the possible negative effect of high ESP.

5. Concluding remarks

The SOC in the irrigated treatment showed a tendency to be higher than in the rain fed soil. The increase in SOC stock at 0–20 cm depth was estimated about 0.221 tn C/ha/year. The increase in SOC in the irrigated soil is due to an increase in crop residue production and the lower loss of OC at the 20–40 cm depth layer could be accredited to a higher root biomass and SOC redistribution in depth. This is due to an increase in SolOC production due to long term irrigation. The small increases in SOC in the irrigated soil could be explained as the balance of increased carbon addition to the soil but also the increase in residue decomposition and SOC mineralization rate.

The AS on the top soil was significantly higher in the irrigated treatment but still would be lower than quasi-pristine nearby soils. The AS was positively related to SOC and soil saline concentration, counteracting the eventual negative effect of exchangeable sodium.

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